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METHODS OF PHYSICAL EXPERIMENT

Determination of Neutron Temperature at Irradiation Positions of IREN

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Abstract—The IREN facility, located in the Frank Laboratory of Neutron Physics at the Joint Institute for Nuclear Research, is an electron accelerator-driven source of intense pulsed neutrons with thermal and resonance energies. It is designed for the application of neutron time-of-flight spectroscopy, which is utilized for measuring neutron interaction cross sections and conducting elemental analysis through (epi)thermal and resonance neutron activation of samples. For the intended purposes, the precise determination of the neutron temperature at the irradiation positions is crucial. This report introduces a methodology for accurately determining the Maxwellian temperature (TM) of the thermal neutron distribution at the irradiation positions located on the outer wall of IREN's neutron production target chamber.

Keywords: IREN facility, NAA, neutron temperature, MCNP code

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INTRODUCTION

The white spectrum neutron source, based on the linear electron accelerator (IREN) and developed at the Laboratory of Neutron Physics of the Joint Institute of Nuclear Physics, is extensively utilized for studying nuclear reactions induced by neutrons with energies ranging from thermal to approximately 20 MeV. This facility is particularly effective for accurately determining the cross-sections of these reactions through high-resolution time-of-flight neutron spectroscopy [1, 2].

IREN has undergone continuous upgrades over the past few years and is currently in its final stages of development. While it is not yet operating at its full design parameters, the facility is still capable of supporting a variety of experiments, including the measurement of neutron-induced reaction cross-sections and neutron activation analysis. For these experiments, accurately determining the neutron temperature at the irradiation points is a critical parameter that must be established prior to conducting the studies.

The neutron temperature at the irradiation position can be determined experimentally [3–5], however, these measurements are often complex and time-consuming. Alternatively, it can be estimated using Monte Carlo simulations, under the assumption that the neutron temperature corresponds to the Maxwellian temperature of the surrounding environment. Currently, several computer simulation programs are available that reliably and accurately simulate the neutron spectrum at the target's irradiation site. MCNP software [6] is one such tool that has been utilized by numerous research groups to calculate the neutron spectrum as an alternative to experimental measurements. The primary objective of this paper is to present a method for determining the thermal neutron temperature at neutron irradiation points.

DETERMINATION OF THE NEUTRON TEMPERATURE AT THE IRRADIATION POSITION

The primary component of the IREN facility is the LUE-200 linear accelerator, which is capable of accelerating electrons to energies of up to 200 MeV. Neutrons are generated by bombarding a target with a high-energy electron beam produced by the LUE-200. When these high-energy electrons strike the target material, they produce a continuous spectrum of bremsstrahlung photons that then interact with the nuclei of the target material, leading to the emission of neutrons.

The main design characteristics of the IREN facility are listed in Table 1, and the energy distribution of the electron beam at the exit window of the LUE-200, measured in October 2023, is presented in Fig. 1.

The photoneutron producing target used in the IREN facility is constructed from a tungsten alloy composed of 90% W, 7% Ni, and 3% Fe, with a density of 18.075 g/cm^3. The target has a height of 100 mm and a diameter of 40 mm, and it is housed within an aluminum tank that has a diameter of 160 mm. A 50 mm layer of water is circulating between the aluminum wall and the tungsten target. This water serves a dual purpose: it slows down neutrons and effectively cools the tungsten target. A detailed drawing of the neutron production target chamber, along with its specifications, is presented in Fig. 2a, while a photograph of the actual setup is shown in Fig. 2b on the right.

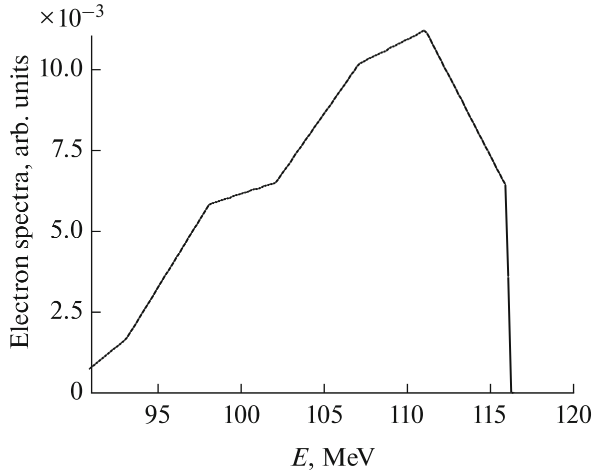

Fig. 1. The energy distribution of electron beam at the exit window of LUE-200, which was measured in October 2023.

Table 1. The primary design parameters of the IREN facility [1]

Parameter	Value
Maximum electron energy	200 MeV
Pulse beam current	1.5–2.0 A
Pusle duration	100–300 ns
Cycle repetition rate	≥150 Hz
Beam power	9–12 kW

To measure the cross sections of neutron-induced reactions, high-purity metal foils were employed as nuclear reaction targets. These foils were affixed to the outer surface of the water moderator tank, as illustrated in Fig. 2b. The neutron temperature at these locations was determined using the MCNP-6 code. For the configuration depicted in Fig. 2a, neutron energy spectra were calculated at various irradiation positions corresponding to different *Z* distances (1, 2, 3, 4, 5, 6, 7, and 8 cm) along the height of the moderator tank. The resulting measured electron distribution is presented in Fig. 1. The *Z*-axis in Fig. 2a is oriented downward from the top of the water moderator tank, aligning with the direction of the incoming electron beam. Additionally, a typical simulated neutron energy spectrum following a cadmium filter of varying thicknesses is shown in Fig. 3.

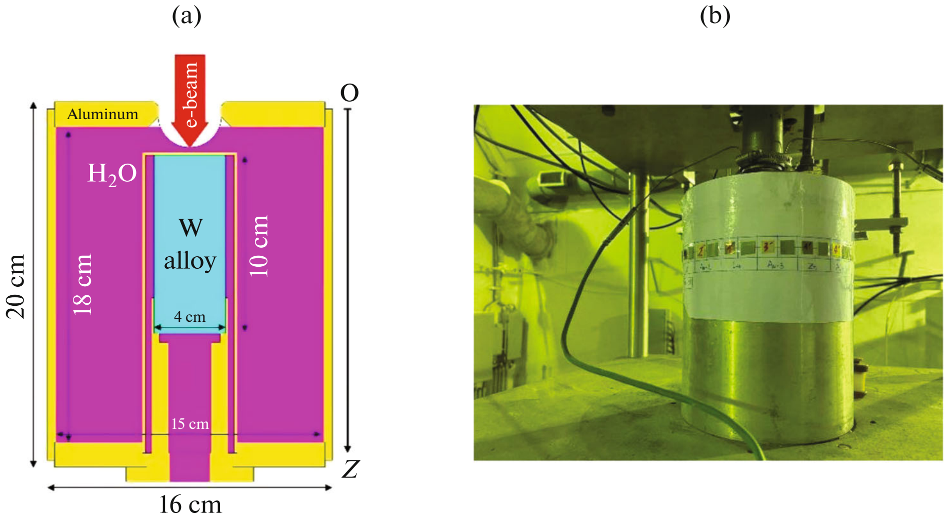

Fig. 2. Detailed drawing of the neutron production target chamber installed at IREN. (a) Detailed drawing of the neutron production target chamber with its specifications, (b) photograph of the actual setup.

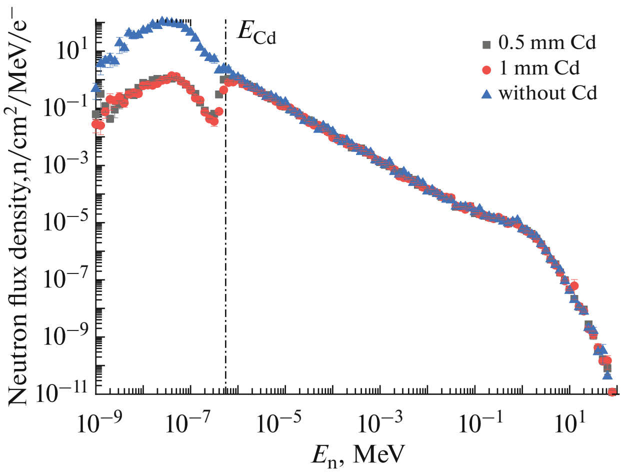

Fig. 3. Neutron flux distribution after cadmium filter of different thicknesses.

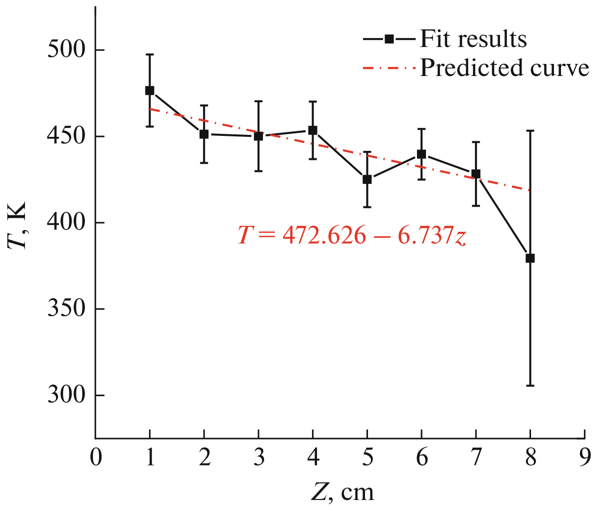

Fig. 5. Variation of the neutron temperature with distance Z.

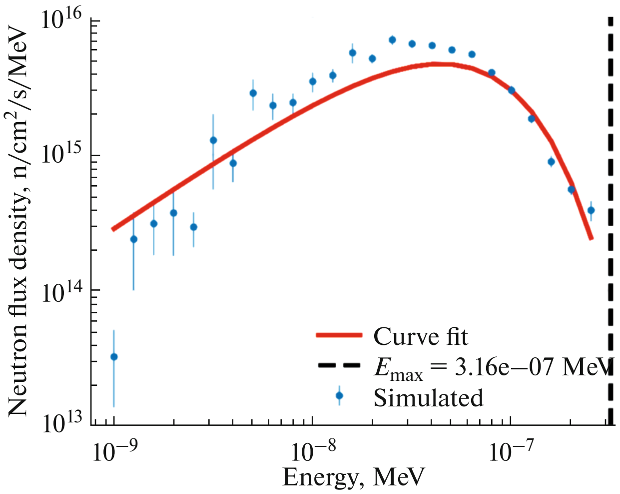

Fig. 4. The neutron flux distribution (dots) without cadmium filter and the fitting curve (solid).

The neutron temperature was determined by fitting the thermal component of the neutron energy spectrum within the range of E_{min} to E_{max} (where $E_{min} = 10^{-9}$ MeV and E_{max} represents the upper limit of thermal neutron energy) for the simulated spectrum without a cadmium filter. This fitting was performed using the Maxwell–Boltzmann (M–B) function, as described below:

$$\varphi_{\mathrm{th}}(E_{\mathrm{n}}) = \Phi_1 \frac{E_{\mathrm{n}}}{(kT_{\mathrm{th}})^2} \exp^{-E_{\mathrm{n}}/kT_{\mathrm{th}}},$$

where, $\varphi_{\mathrm{th}}(E_{\mathrm{n}})$ is neutron spectrum, the parameter Φ_1 is constant expressing the intensity of thermal neutron flux, E_{n} is neutron energy, T_{th} is temperature of neutrons, and k is the Boltzmann constant.

The energy region of the thermal neutron spectrum used to determine the neutron temperature, along with the fitted M–B function (1), is illustrated in Fig. 4. In this figure, the dots represent the simulated values, while the solid curve indicates the fitted distribution. The results obtained from this analysis are presented in Table 2.

It is important to note that the determined value of the neutron temperature remains relatively constant when the E_{max} value is varied within the range of 0.1 to 1 eV. The neutron temperature values at different irradiation positions (Z = 1, 2, ..., 8 cm) on the outer surface of the water moderator tank are provided in Table 3 and illustrated in Fig. 5. From both Table 2 and Fig. 5,

Table 2. TM at the irradiation position with Z = 5 cm

E_{max}, eV	T_{th}, K
0.1	426 ± 19
0.55	425 ± 15
1	425 ± 15
Average	425.3 ± 16

Table 3. TM at different irradiation positions Z

Z, cm	T_M, K
1	477 ± 21
2	451 ± 16
3	450 ± 20
4	453 ± 17
5	425 ± 16
6	440 ± 15
7	428 ± 18
8	379 ± 74

it is clear that the neutron temperature varies significantly across the different irradiation positions.

CONCLUSIONS

This report presents detailed findings on the neutron temperature at various irradiation positions on the external surface of the water moderator tank within the neutron production chamber at the IREN facility. The methodology employed involves simulating the neutron spectrum using the Monte Carlo method, specifically through the MCNP-6 code. The results reveal significant variations in neutron temperatures across the different irradiation positions. Therefore, it is essential to determine this parameter before conducting experiments that utilize neutrons generated by the IREN facility. This assessment is critical for ensuring the accuracy and reliability of the experimental outcomes.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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